Sensitivity of river discharge to ENSO

Ward, P.J.; Beets, W.; Bouwer, L.M.; Aerts, J.C.J.H.; Renssen, H.

published in
Geophysical Research Letters
2010

DOI (link to publisher)
10.1029/2010GL043215

document version
Publisher's PDF, also known as Version of record

GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L12402, doi:10.1029/2010GL043215, 2010

Click Here for Full Article

Sensitivity of river discharge to ENSO

Philip J. Ward,[1] Wisse Beets,[1] Laurens M. Bouwer,[1] Jeroen C. J. H. Aerts,[1] and Hans Renssen[2]

Received 11 March 2010; revised 28 April 2010; accepted 6 May 2010; published 16 June 2010.

[1] El Niño Southern Oscillation (ENSO) has significant impacts on streamflows around the world. While many studies have assessed correlations, an assessment of the magnitude of this impact is lacking, and little is known of ENSO's impact on extreme discharges. We use a daily discharge dataset to provide a global assessment of the sensitivity of annual mean and flood discharges to ENSO, and a gridded climate dataset to assess the global impact of ENSO on precipitation and temperature. We find that, on average, for the stations studied ENSO has a greater impact on annual high-flow events than on mean annual discharge, especially in the extra-tropics. The quantification of ENSO impacts provides relevant information for water-management, allowing the identification of problem areas and providing a basis for risk assessments. **Citation:** Ward, P. J., W. Beets, L. M. Bouwer, J. C. J. H. Aerts, and H. Renssen (2010), Sensitivity of river discharge to ENSO, *Geophys. Res. Lett.*, *37*, L12402, doi:10.1029/2010GL043215.

1. Introduction

[2] The relationship of the El Niño Southern Oscillation (ENSO) to global climate patterns is of interest to scientists and policy-makers due to its effects on natural and societal systems [*Schmidt et al.*, 2001]. ENSO results from interactions between large scale atmospheric and oceanic circulation. The mainly oceanic component, El Niño (EN), refers to the appearance of anomalously warm water over the eastern equatorial Pacific Ocean. The mainly atmospheric component, the Southern Oscillation, is associated with substantial east-west shifts in the tropical atmospheric circulation between the Indian and West Pacific Oceans and the East Pacific Ocean. Under so-called neutral conditions, the eastern Pacific Ocean surface is relatively cool, and is associated with descending atmospheric motion and high surface pressure, whilst rising air, low surface pressure, and heavy rains prevail over the relatively warm waters of the Indonesian archipelago, the western Pacific, southeast Africa, and the Amazon area (so-called Walker circulation). Other regions with sinking atmospheric motion are the equatorial Atlantic and western Indian Ocean. During EN, warming of surface waters in the central and eastern equatorial Pacific occurs, causing enhanced convection and rainfall in this region, whilst the western Pacific is relatively cool, leading to reduced convection and drier conditions over Indonesia and Australia. During La Niña (LN), the neutral conditions described above are intensified [*Peixoto and Oort*, 1992]. ENSO affects temperatures and precipitation in other regions around the globe through climatic teleconnections [*Kiladis and Diaz*, 1989].

[3] For water management, interannual variations in hydrology play a key role in planning. Scores of studies have shown that ENSO-driven changes in temperature and precipitation correlate well with mean annual and seasonal river discharge [*Dettinger et al.*, 2000, and references therein]. *Dettinger and Diaz* [2000] and *Dettinger et al.* [2000] used global datasets to examine the relationship between ENSO and mean discharge around the world. They found that ENSO variations are correlated with discharge in many parts of the Americas, Australia, and northern Europe, and parts of Africa and Asia. However, most of the natural and societal problems associated with the effects of ENSO on river flow are felt through its effects on extreme events, such as floods and droughts. A few studies at the basin or country scale have assessed the impacts of ENSO on low-flows [e.g., *Moss et al.*, 1994; *Piechota and Dracup*, 1999; *Whetton et al.*, 1990], or floods [e.g., *Cayan and Webb*, 1992; *Cayan et al.*, 1999; *Foley et al.*, 2002; *Waylen and Caviedes*, 1986; *Whetton et al.*, 1990], but these only examine a few locations, and a global or regional scale analysis is lacking. Furthermore, to date no sensitivity analysis has been carried out to assess the magnitude of the impact of ENSO fluctuations on river discharge.

[4] In this paper we use a global dataset of daily river discharge observations, and a gridded dataset of monthly precipitation and temperature, to provide the first global assessment of the sensitivity of mean and high-flows of rivers to ENSO-driven interannual climate variability.

2. Methodology

2.1. Data

[5] Daily discharge data were taken from the Global Runoff Database (supplied by The Global Runoff Data Centre (GRDC), http://www.bafg.de/cln_007/nn_266918/GRDC), for all stations with mean annual discharge in excess of 100 m^3s^{-1}, and a record length of 25 years or longer (609 stations). The GRDC operates under the auspices of the World Meteorological Organization, and contributes to several major international research programs. Due to the availability of daily discharge data with sufficiently long records in the public domain, coverage is skewed towards certain regions (e.g., North America, Europe, eastern Australia). To increase coverage in other regions, we used time-series of maximum daily discharge per year from *UNESCO* [1976] and IAHS [*Herschy*, 2003; *Rodier and Roche*, 1984], providing thirteen stations. The number of gauging stations used for each year

[1]Institute for Environmental Studies, VU University, Amsterdam, Netherlands.
[2]Department of Earth Sciences, VU University, Amsterdam, Netherlands.

0094-8276/10/2010GL043215

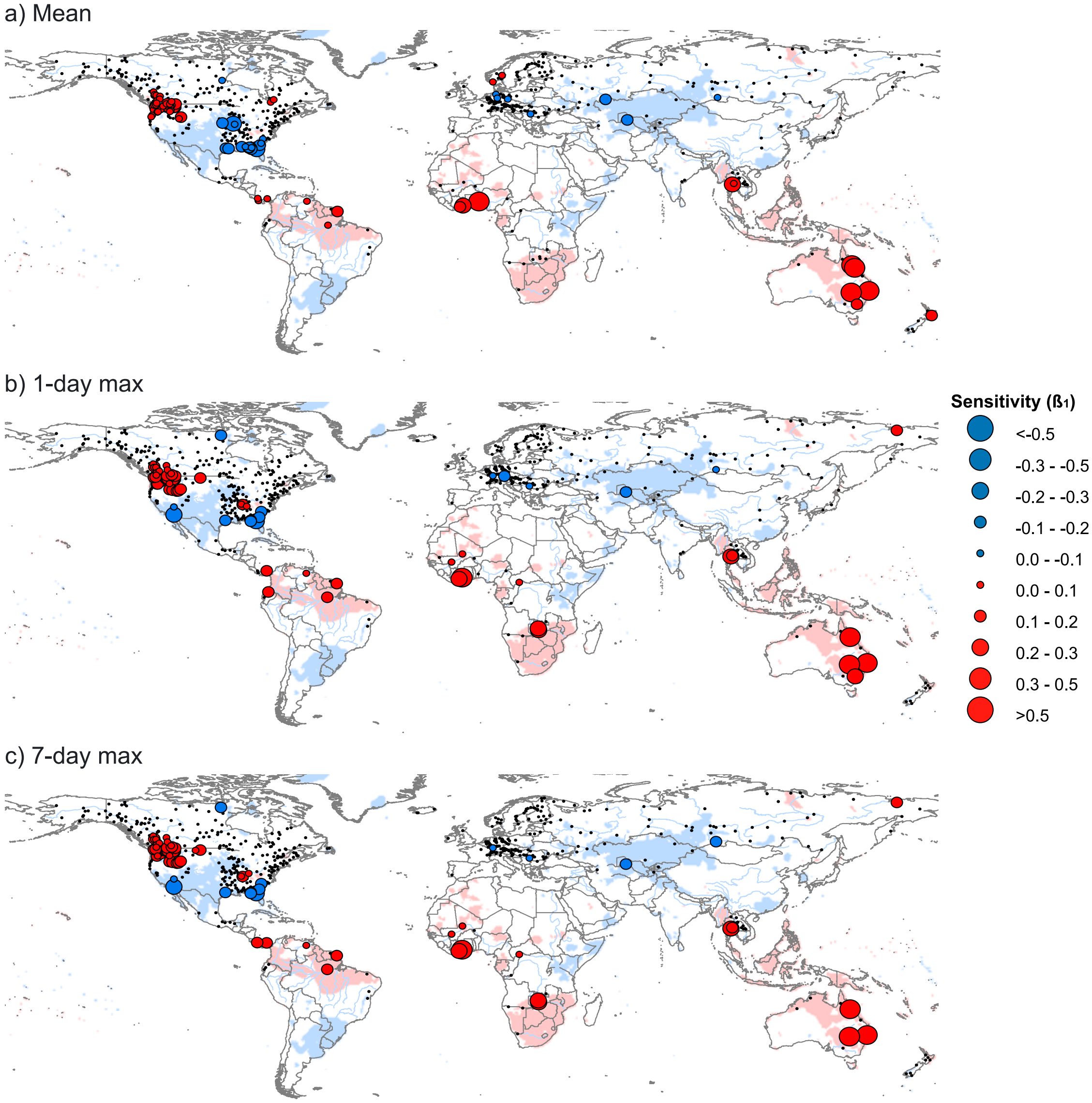

Figure 1. (a) Sensitivity (β_1) of mean annual discharge, (b) annual 1-day maximum discharge, and (c) annual 7-day maximum discharge (for hydrological years) to DJF SOI. Small black dots indicate stations with no statistically significant correlation; colored circles indicate stations with statistically significant correlations ($\alpha = 0.05$). Blue circles indicate negative correlation (wetter EN/drier LN), and red circles indicate positive correlation (drier EN/wetter LN); the size of the circle represents the sensitivity (see legend). A blue (red) shaded background indicates areas where annual (hydrological year) precipitation shows a significant negative (positive) correlation with DJF SOI. These correlations of precipitation with SOI, as well as temperature with SOI, are shown in more detail in Figure S3.

is shown in Figure S1 of the auxiliary material.[1] The geographical distribution is shown in Figure 1; the coverage is fairly good, although there are notable exceptions (Indian subcontinent, north Africa, southern South America, Indonesian archipelago, China). Monthly data for these regions are more readily available; however, in this paper daily data are required. For global climate, we used gridded datasets of monthly precipitation and temperature from the CRU TS 2.0 dataset [*Mitchell and Jones*, 2005] (0.5° × 0.5°) for the hydrological years 1902–2000.

[6] We used the Southern Oscillation Index (SOI) as an indicator of the mode of the ENSO cycle. Monthly SOI values (1866–2008) were taken from the Climatic Research Unit (CRU) (http://www.cru.uea.ac.uk/cru/data/soi.htm). During EN (LN) events the SOI is negative (positive). To assess the robustness of the results when using other indices of ENSO, we also carried out the analyses with the (inverse) NINO3.4 (http://climexp.knmi.nl) and the (inverse) Global SST ENSO (http://www.jisao.washington.edu/data_sets/globalsstenso/) indices.

2.2. Methods

[7] For each station and hydrological year (October–September), we calculated mean annual discharge, and 1-day

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL043215.

Table 1. Percentage of Gauging Stations for Which There Are Positive and Negative Correlations between DJF SOI and Mean Annual Discharge, or Annual 1-Day or 7-Day Maximum Discharge for Hydrological Years[a]

	Percent of Stations With Positive (Negative) Correlations		
	All Locations	Tropical	Extratropical
Mean annual discharge	71 (29)	100 (0)	65 (35)
Annual 1-day maximum discharge	80 (20)	100 (0)	74 (26)
Annual 7-day maximum discharge	81 (19)	100 (0)	75 (25)

[a]Results are shown only for stations for which the correlation is statistically significant (α = 0.05).

and 7-day maximum discharge, and assessed the correlation (r) between these parameters and SOI for the period December–February (DJF). We used the DJF SOI because: (a) during this period EN generally reaches its full development; and (b) it was used by *Dettinger et al.* [2000] and *Dettinger and Diaz* [2000], thus allowing for comparison. We assessed the sensitivity (β_1) of changes in these discharge parameters to changes in DJF SOI, using [*Bouwer et al.*, 2008]:

$$\ln(q_i) = \beta_0 + \beta_1 a_i + \varepsilon_i \tag{1}$$

where q_i is observed mean annual discharge, or annual 1-day or 7-day maximum discharge in hydrological year i; a_i is DJF value of SOI in hydrological year i; β_0 and β_1 are coefficients; and ε_i is the error. β_1 represents the sensitivity of discharge to SOI, whereby β_1 * 100 represents the percentage change in discharge (q_i) per unit change SOI. We also carried out the analyses for calendar years (i.e. January–December), since *Kiladis and Diaz* [1989] show that ENSO correlates most strongly with precipitation in the boreal autumn (September–November) in several (sub-) tropical regions. Correlation (r) was also assessed between the discharge data and the (inverse) NINO 3.4 and global SST ENSO indices, and between the SOI index and the gridded values of precipitation and temperature.

[8] Discharge can be affected by changes in several factors, such as land-use and water management infrastructure [*Ward et al.*, 2008]; we are interested in detecting impacts of interannual climate oscillations. Even in areas where structural water management measures have been taken, signals of regional atmospheric variability are found, for instance in flood frequency records [*Florsheim and Dettinger*, 2007]. However, to assess the possible impacts of water infrastructure on discharge-SOI correlations, we also carried out the analyses for the two separate periods 1921–1950 and 1951–1980. The mean and variance of DJF SOI are not statistically different in these two periods (t-test, p = 0.768; F-test, p = 0.900), but they represent periods with different levels of water infrastructure. *Chao et al.* [2008] show that global reservoir water impoundment increased slowly in the first half of the 20th century (ca. 800 km^3 by 1950), and rapidly thereafter (ca. 6,500 km^3 by 1980).

3. Results and Discussion

[9] The sensitivity of mean annual discharge, and annual 1-day and 7-day maximum discharge, to changes in DJF SOI are shown in Figure 1. For all of the tropical stations (i.e., between 23.4°N and 23.4°S) with significant correlation, the sign of that correlation is positive for all three discharge parameters (Table 1). As explained in the introduction, the relatively dry conditions in tropical areas during EN events are associated with a disturbance of the Walker circulation over the equatorial Pacific Ocean.

[10] The average sensitivity at the gauging stations studied (with significant correlation) to SOI variations is significantly greater for annual 1-day and 7-day maximum discharge than for mean annual discharge (Table 2), although for tropical rivers only, there is no statistical difference. These values should not be interpreted as a ‘global’ sensitivity of continental discharges to ENSO, since there are several important regions for which no data are available, but they do show that the impact of ENSO on discharge is stronger on high-flows than average flows in many parts of the world.

3.1. Regional Sensitivities of Mean Discharge

[11] The regional distribution of significant correlations for mean annual discharge (Figure 1a) generally follows that of *Dettinger and Diaz* [2000]. The results are robust to the choice of ENSO index; although there are stations with different results according to the index used, the overall pattern is similar (results for annual 1-day maximum discharge are shown in Figure S2). The map of correlations between mean discharge and SOI closely resembles that of annual precipitation and SOI (Figures S3 and S1 (background)), on which the well known effects of ENSO on precipitation [e.g., *Kiladis and Diaz*, 1989] are reflected. However, this is not the

Table 2. Average Sensitivity (β_1) of Mean Annual Discharge, or Annual 1-Day or 7-Day Maximum Discharge, to SOI Variations[a]

	Average β_1 Value		
	All Locations	Tropical	Extratropical
Mean annual discharge	0.11 (n = 82)	0.19 (n = 13)	0.10 (n = 69)
Annual 1-day maximum discharge	0.14 (n = 69)	0.17 (n = 15)	0.14 (n = 54)
Annual 7-day maximum discharge	0.14 (n = 68)	0.17 (n = 15)	0.14 (n = 53)

[a]Results are shown only for stations for which the correlation is statistically significant (α = 0.05); the number of observations (n) is shown in brackets. The difference in the average sensitivity between mean annual discharge and annual maximum discharge is significant for all locations and extratropical rivers (t-test, p = 0.036 and 0.003 respectively), but not significant for tropical rivers (t-test, p = 0.584). The difference in the average sensitivity between mean annual discharge and annual maximum 7-day discharge is significant for all locations and extratropical rivers (t-test, p = 0.033 and 0.003 respectively), but not significant for tropical rivers (t-test, p = 0.645).

case for northwest USA/southwest Canada. Here, discharge and SOI show significant correlations, whilst precipitation only shows a significant correlation with SOI along a small stretch of coast around the border. However, the precipitation data do show a significant negative correlation with SOI during the winter half year, which may be partly responsible for the lower (higher) discharge during EN (LN) events. Moreover, temperature shows a significant positive correlation with SOI, so that increased (decreased) temperatures during EN (LN) may also contribute through their effects on evapotranspiration.

[12] Compared to the map of *Dettinger and Diaz* [2000], several new findings are made. Our results show three stations with significant positive correlation in West Africa (Bandama, Comoé, Ouémé). These are not assessed by *Dettinger and Diaz* [2000], and the other stations in West Africa are in agreement with the former study (no significant correlations for mean discharge). West Africa is discussed further in Section 3.2. Our results show negative correlations in the southeastern corner of the USA (southern Georgia, Florida, and Gulf Coast of Texas, Mississippi, and Alabama). These stations are located more southerly than those in the eastern USA analyzed by *Dettinger and Diaz* [2000], and show a difference in the response of rivers in the far southeastern corner of the USA to rivers further north along the eastern seaboard. Our findings are in agreement with results from Florida [e.g., *Schmidt et al.*, 2001], and can be explained by ENSO teleconnections which cause: (a) an equatorial (poleward) displacement of the mid-latitude jet during EN (LN) events, which increases (decreases) frontal precipitation; and (b) advection of moisture from the tropical Pacific by the subtropical jet stream into southeastern USA during EN winters [*Ropelewski and Halpert*, 1986]. Figure S3 shows this strong negative SOI- precipitation correlation. Of the stations used in our study in southwestern USA, none show a significant mean discharge-SOI correlation, despite a strong precipitation-SOI correlation (also for the period 1921–1950). The stations used in this study are located on the region's major rivers (Colorado, Sacramento, San Joaquin), which have a long history of human interference. For example, the combined reservoir storage capacity of large dams in these basins was ca. 50 km^3 by 1950 [*ICOLD*, 2003]. These interferences may dampen any signal of discharge correlations with ENSO. The analyses were also carried out for stations in the GRDC database with monthly discharge data only, and several negative correlations were found, as per *Dettinger et al.* [2001].

[13] The sensitivity of mean discharge to SOI is greatest in eastern Australia. The lack of available daily discharge data for the southern part of South America and the Indonesian archipelago render an assessment in those regions impossible. However, southern South American basins are relatively well covered by existing basin scale assessments, and by *Dettinger and Diaz* [2000], which show negative correlations.

[14] Using calendar year discharge, there are generally few changes in the pattern. The main difference is in West Africa, where sensitivities of the Ouémé and Comoé are greater, due to a strong positive correlation between DJF SOI and October precipitation in the region. On the Indian subcontinent, which encounters a monsoonal rainfall regime, none of the (few) rivers studied show a significant correlation with SOI (for hydrological or calendar years); this is also reflected in our map of precipitation-SOI correlations. These results are in contrast to those of *Whetton et al.* [1990], who found a significant positive correlation ($r = 0.47$) between Krishna calendar year discharge and the SO index between 1901–1960.

3.2. Regional Sensitivities of High-Flows

[15] The sensitivities of annual 1-day and 7-day maximum discharge to DJF SOI (Figures 1b and 1c) show little difference to each other, and show many similar geographical patterns to those of mean annual discharge. Eastern Australia remains the most sensitive region. However, there are regions, especially in the extra-tropics (Table 2), where the sensitivity of high-flows to ENSO is greater than that of mean annual discharge; these are discussed in this section.

[16] In northwest USA/southwest Canada, all three discharge parameters show significant positive correlations with SOI. The number of significant correlations, and the sensitivity, is greater for high-flows. This can be explained by decreased (increased) early spring precipitation during EN (LN) events (seen in the correlation results of precipitation-SOI for February and March), due to changes in the storm track over the Pacific [*Shabbar*, 2006]. The resulting increase in storm activity during the spring snowmelt season (when discharges are high) may lead to increased peak discharges, especially since our analyses show warmer (colder) conditions in the region at that time. The southward migration of storm tracks also explains the negative correlations of annual 1-day and 7-day maximum discharge and SOI on the downstream stations of the Colorado river (increased winter storminess). *Cayan and Webb* [1992] and *Cayan et al.* [1999] show that flooding is more common in southwest USA in EN years than in neutral/LN years; the number of correlations found by *Cayan et al.* [1999] is much larger, since they used gauging stations selected for minimal effects of upstream artificial influence.

[17] Several studies show positive discharge-ENSO correlations in northern South America, and negative correlations in southern South America [e.g., *Dettinger and Diaz*, 2000; *Dettinger et al.*, 2000; *Kiladis and Diaz*, 1989]. Here, we find annual high-flows in northern South America to have a similar sensitivity to ENSO compared to mean discharge. The lack of daily discharge data availability for southern South America makes an assessment of this sensitivity impossible in this study.

[18] High-flows at several stations in West Africa show significant positive correlations with DJF SOI (Figures 1b and 1c). The relationships in this region are somewhat complicated, since they are not consistent when using other ENSO-indices (Figure S2). Significant correlations with high-flows are seen in the region for all three ENSO indices, but the stations with significant correlations differ between indices. The most persistent signals are for the stations along the coast, since this region also shows a strong positive correlation between DJF SOI and hydrological year precipitation (see Figure S3), and an even stronger relationship for calendar years. Several studies have evaluated ENSO-influence on rainfall in West Africa; some suggest minimal influence, others suggest lower (higher) rainfall in EN (LN) years [*Moron and Ward*, 1998]. *Joly and Voldoire* [2009] showed that a significant part of the interannual variability of the West Africa Monsoon can be explained by ENSO, possibly related to: (a) the displacement of the Walker circulation to the east,

and thus atmospheric subsidence over West Africa; and (b) a weakening of the Tropical Easterly Jet. All of these results show that more research is needed in this region, particularly given the ambiguities found, and the dependence of a large proportion of the region's population on (rainfed) agriculture.

3.3. Assessment of Pre- and Post-1950 ENSO Relationships

[19] The correlations for the periods 1921–1950 and 1951–1980 generally show the same geographical patterns, except in northern Europe (Figure S4). Several stations in Germany and the Benelux countries show significant negative correlation between mean discharge and SOI in 1921–1950, yet no correlation in 1951–1980, whilst several Scandinavian stations show significant positive correlation in the former period and no significant correlation in the latter. Our climate analyses show that in 1921–1950 a strong positive correlation existed between SOI and precipitation (EN drier/LN wetter) in a large part of Scandinavia, but not in 1951–1980. There is no significant precipitation-SOI correlation for either period in Germany, the Benelux countries, or upstream locations. However, there is a strong positive correlation between temperature and SOI (in the region in 1921–1950, but not in 1951–1980. This means that in the period 1921–1950, EN (LN) years were cooler (warmer), which would lead to decreased (increased) evapotranspiration and increased (decreased) discharge. Therefore, the changes in discharge-SOI correlation between 1921–1950 and 1951–1980 in Europe appear to be attributable to changes in the relationship between ENSO and climate, rather than changes in water management measures such as dams.

4. Implications and Conclusions

[20] Past studies have demonstrated that ENSO correlates well with the mean river discharge around the globe. Establishing such correlations is important, but the quantification of the impact on mean and peak discharge helps to quantify the potential impacts of climatic variations on hydrology, and may provide a basis for risk assessments. In this paper we have carried out a quantified assessment of such impacts and have shown that on average, for the rivers studied, ENSO has a greater impact on annual high-flows than on mean annual discharge. There are several important regions not covered, since the dataset used here, whilst global, does not have a uniform coverage of the entire globe. Our findings do, however, highlight the need for further research in those areas for which data are not readily available in global datasets, but may be available through national or local (hydrological) institutions. The results also highlight the need for further research into the impacts of ENSO on river discharge in West Africa.

[21] These findings are important for water management, both in terms of the negative (e.g. economic damage and loss of life) and positive (e.g. dispersal of nutrients on floodplains, replenishment of reservoirs) effects of changes in runoff and flooding, and suggest that more research at the basin scale is needed to assess the ENSO-impacts on extreme discharge events, rather than just mean discharge. There are many other large-scale atmospheric processes that can have both local and remote effects on discharge [*Bouwer et al.*, 2008; *Pizarro and Lall*, 2002]. More research into the individual and combined effects of these processes worldwide may assist in long-term forecasting for agriculture and flood risk management.

[22] **Acknowledgments.** The Global Runoff Data Centre (GRDC) kindly provided the majority of the river discharge data. We thank Sarah Tynan for assisting with literature research, and three anonymous reviewers for their useful comments on an earlier version of the manuscript.

References

Bouwer, L. M., J. E. Vermaat, and J. C. J. H. Aerts (2008), Regional sensitivities of mean and peak river discharge to climate variability in Europe, *J. Geophys. Res.*, *113*, D19103, doi:10.1029/2008JD010301.

Cayan, D. R., and R. H. Webb (1992), El Niño/Southern Oscillation and streamflow in the western United States, in *El Niño and Paleoclimatic Aspects of the Southern Oscillation*, edited by H. F. Diaz and V. Markgraf, pp. 29–68, Cambridge Univ. Press, Cambridge, U. K.

Cayan, D. R., K. T. Redmond, and L. G. Riddle (1999), ENSO and hydrologic extremes in the western United States, *J. Clim.*, *12*, 2881–2893, doi:10.1175/1520–0442(1999)012<2881:EAHEIT>2.0.CO;2.

Chao, B. F., Y. H. Wu, and Y. S. Li (2008), Impact of artificial reservoir water impoundment on global sea level, *Science*, *320*, 212–214, doi:10.1126/science.1154580.

Dettinger, M. D., and H. F. Diaz (2000), Global characteristics of stream flow seasonality and variability, *J. Hydrometeorol.*, *1*, 289–310, doi:10.1175/1525-7541(2000)001<0289:GCOSFS>2.0.CO;2.

Dettinger, M. D., D. R. Cayan, and G. J. McCabe (2000), Multiscale streamflow variability associated with El Niño/Southern Oscillation, in *El Niño and the Southern Oscillation-Multiscale Variability and Global and Regional Impacts*, edited by H. F. Diaz and V. Markgraf, pp. 113–147, Cambridge Univ. Press, Cambridge, U. K.

Dettinger, M. D., D. S. Battisti, R. D. Garreaud, G. J. McCabe, and C. M. Bitz (2001), Interhemispheric effects of interannual and decadal ENSO-like climate variations on the Americas, in *Interhemispheric Climate Linkages: Present and Past Climates in the Americas Their Societal Effects*, edited by V. Markgraf, pp. 1–16, Academic, San Diego, Calif.

Florsheim, J. L., and M. D. Dettinger (2007), Climate and floods still govern California levee breaks, *Geophys. Res. Lett.*, *34*, L22403, doi:10.1029/2007GL031702.

Foley, J. A., A. Botta, M. T. Coe, and M. H. Costa (2002), El Niño-Southern Oscillation and the climate, ecosystems and rivers of Amazonia, *Global Biogeochem. Cycles*, *16*(4), 1132, doi:10.1029/2002GB001872.

Herschy, R. (2003), *World Catalogue of Maximum Observed Floods*, *IAHS Publ.*, 284.

ICOLD (2003), *Word Register of Dams* [CD-ROM], ICOLD, Paris.

Joly, M., and A. Voldoire (2009), Influence of ENSO on the West African Monsoon (WAM): Temporal aspects and atmospheric processes, *J. Clim.*, *22*, 3193–3210, doi:10.1175/2008JCLI2450.1.

Kiladis, G. N., and H. F. Diaz (1989), Global climatic anomalies associated with extremes in the Southern Oscillation, *J. Clim.*, *2*, 1069–1090, doi:10.1175/1520-0442(1989)002<1069:GCAAWE>2.0.CO;2.

Mitchell, T. D., and P. D. Jones (2005), An improved method of constructing a database of monthly climate observations and associated high-resolution grids, *Int. J. Climatol.*, *25*, 693–712, doi:10.1002/joc.1181.

Moron, V., and M. N. Ward (1998), ENSO teleconnections with climate variability in the European and African sectors, *Weather*, *53*, 287–295.

Moss, M. E., C. P. Pearson, and A. I. McKerchar (1994), The Southern Oscillation Index as a predictor of the probability of low streamflows in New Zealand, *Water Resour. Res.*, *30*, 2717–2723, doi:10.1029/94WR01308.

Peixoto, J. P., and A. H. Oort (1992), *Physics of Climate*, Am. Inst. of Phys., New York.

Piechota, T. C., and J. A. Dracup (1999), Long-range forecasting using El-Niño Southern Oscillations indicators, *J. Hydrol. Eng.*, *4*, 144–151, doi:10.1061/(ASCE)1084-0699(1999)4:2(144).

Pizarro, G., and U. Lall (2002), El Niño and floods in the US West: What can we expect?, *Eos Trans. AGU*, *83*, 349.

Rodier, J. A., and M. Roche (1984), *World Catalogue of Maximum Observed Floods*, *IAHS Publ.*, 143.

Ropelewski, C. F., and M. S. Halpert (1986), North American precipitation and temperature patterns associated with the El Niño Southern Oscillation (ENSO), *Mon. Weather Rev.*, *114*, 2352–2362, doi:10.1175/1520-0493(1986)114<2352:NAPATP>2.0.CO;2.

Schmidt, N., E. K. Lipp, J. B. Rose, and M. E. Luther (2001), ENSO influences on seasonal rainfall and river discharge in Florida, *J. Clim.*, *14*, 615–628, doi:10.1175/1520-0442(2001)014<0615:EIOSRA>2.0.CO;2.

Shabbar, A. (2006), The impact of El Niño-Southern Oscillation on the Canadian climate, *Adv. Geosci.*, *6*, 149–153, doi:10.5194/adgeo-6-149-2006.

UNESCO (1976), World catalogue of very large floods, *Stud. Rep. Hydrol. 21*, UNESCO Press, Paris.

Ward, P. J., H. Renssen, J. C. J. H. Aerts, R. T. van Balen, and J. Vandenberghe (2008), Strong increases in flood frequency and discharge of the River Meuse over the late Holocene: Impacts of long-term anthropogenic land use change and climate variability, *Hydrol. Earth Syst. Sci.*, *12*, 159–175, doi:10.5194/hess-12-159-2008.

Waylen, P. R., and C. N. Caviedes (1986), El Niño and annual floods on the North Peruvian littoral, *J. Hydrol.*, *89*, 141–156, doi:10.1016/0022-1694(86)90148-4.

Whetton, P. H., D. A. Adamson, and M. A. J. Wilson (1990), Rainfall and river flow variability in Africa, Australia and East Asia linked to El Niño-Southern Oscillation indices, *Geol. Soc. Aust. Symp. Proc.*, *1*, 71–82.

J. C. J. H. Aerts, W. Beets, L. M. Bouwer, and P. J. Ward, Institute for Environmental Studies, Faculty of Earth and Life Sciences, VU University, Amsterdam, De Boelelaan 1085, NL-1081 HV Amsterdam, Netherlands. (philip.ward@ivm.vu.nl)

H. Renssen, Department of Earth Sciences, VU University, De Boelelaan 1085, NL-1081 HV Amsterdam, Netherlands.